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Generation of a periodic sequence of sub-gigawatt ultrashort pulses at a frequency of 12.5 GHz with a repetition period of 4 ns in the superradiance mode of a relativistic backward wave oscillator

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The experiment implements a mode for generating a periodic sequence of ultrashort superradiance pulses of a relativistic backward wave oscillator at a frequency of 12.5 GHz. During a single pulse of the electron beam current (40 ns), eight pulses are generated with a duration of each at half the peak power level of about 1.0 ns and a repetition period of 4.0 ns (repetition frequency of 250 MHz). The peak power of such pulses was in the range 0.2−0.65 GW, and the corresponding conversion coefficients, defined as the ratio of peak power to electron beam power, 0.3−0.6. At the same time, there was a correlation between the first and subsequent pulses of the sequence and a strict periodicity of their sequence.

Keywords: Relativistic backward wave oscillator, superradiance, high-current electron beam.

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Studies focused on the practical implementation of microwave generation of periodic sequences of ultrashort pulses (USPs) with a duration of several oscillation periods and a repetition rate of several hundred megahertz in various frequency ranges have gained momentum in recent years [1–4]. The interest in such research stems from the results of studies into the electromagnetic compatibility of electronic devices, where the capacity of microwave radiation of this kind to penetrate efficiently into electronic equipment via its reception paths was noted [5]. Various circuit designs implementing this generation mode have already been developed and examined in the field of high-power microwave electronics. Their common feature is the presence of a feedback circuit that sets the repetition period of microwave pulses. Since each formed USP is involved in the formation of the next one, a correlation between pulses in a sequence was first predicted theoretically [1,3] and then demonstrated experimentally [2]. This may be particularly relevant to the development of radars with nanosecond sounding pulses [6,7].

This work is a continuation of a series of theoretical and experimental studies into the generation of USP sequences based on a relativistic backward wave oscillator operating in the superradiance mode [8]. The aims of the study were as follows: increase the number of USPs at a given duration of a high-current electron beam current pulse (about 40 ns); demonstrate stable operation of a microwave generator in the high-current electron accelerator mode with a repetition rate up to 50 Hz; and verify experimentally the existence of correlation between microwave pulses in a sequence. A microwave generator design for an oscillation frequency of 12.5 GHz with a feedback circuit providing a USP repetition period in a sequence of about 4 ns was developed for this purpose.

A superradiant relativistic backward wave oscillator with wave reflectors at the edges of the interaction space was examined experimentally. The operating principle of this design was detailed in [3]. The device featured two reflectors. One was located at the entrance to the slow-wave structure on the cathode assembly side and ensured total reflection of incident microwave radiation. Another reflector, which was located at the generator output on the electron collector side, routed approximately 10% of power back to the slow-wave structure. This design was tested successfully in experiments at a generation frequency of 10 GHz [4]. Its operation relies on the mechanism of cumulative energy extraction from an electron beam by a superradiance pulse that originates at the collector end of the device and propagates toward an undisturbed electron flux.

Numerical modeling of operation of the microwave generator was performed using the axisymmetric version of the KARAT PiC code [9]. With an electron beam current of 4.5 kA, an accelerating voltage of 300 kV, a 40-ns-long current pulse with a front of 5 ns, and a guiding magnetic field of 2.0 T, a sequence of ultrashort microwave pulses was generated at frequency $F_{gen} \approx 12.5$ GHz. The calculated pulse repetition rate was 250 MHz. The peak powers of all USPs were close to 1 GW. Figure 1 and the inset show an oscilloscope record of the electric field of a wave at the generator output and normalized correlation function $C(t)$ obtained after processing for the first (test) pulse $A_1(t)$ and

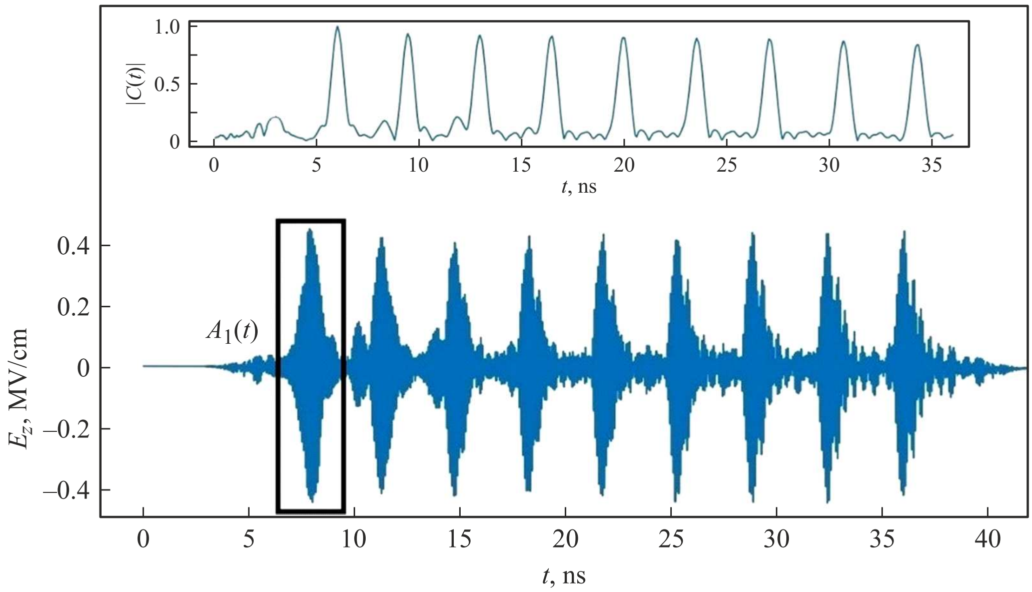

Figure 1. Calculated time dependence of the longitudinal component of the high-frequency electric field (E_z) on the system axis near the microwave absorber. The inset shows the envelope of the modulus of the normalized correlation function.

full sequence of pulses $A(t)$:

$$C(t) = \frac{1}{T_{rep}} \int_0^{T_{rep}} A_1(t')A^*(t'-t)dt'$$

$$\times \left(\frac{1}{T_{rep}} \int_0^{T_{rep}} |A_1(t')|^2 dt' \frac{1}{T_{rep}} \int_t^{T_{rep+t}} |A(t')|^2 dt' \right)^{-1/2},$$

where $T_{rep} \approx 4$ ns is the pulse repetition period. A SINUS high-current pulse generator with a triple forming line, which produced voltage pulses with an amplitude up to 330 kV and a duration of about 40 ns, was used as a high-voltage source in experimental studies. A tubular relativistic electron beam was emitted from an edge explosive emission cathode with a diameter of 28 mm and shaped in a coaxial vacuum diode with magnetic insulation. The magnetic field transporting the beam through the electrodynamic system of the microwave generator was produced by a DC solenoid with oil-cooled coils and a uniform magnetic field section 450 mm in length. A directional coupler based on a circular waveguide was positioned at the output of the microwave generator. In order to monitor the USP amplitude and shape, the signal from the coupler was transmitted to a vacuum-tube detector and recorded by a Tektronix TDS 7404 oscilloscope (4 GHz, 20 GS/s). A Keysight (Agilent) UXR0134A (13 GHz, 128 GS/s) oscilloscope was used to record radio signals from the coupler.

With a vacuum diode voltage of 280 kV, a beam current of 3.8 kA, and a guiding magnetic field of 1.8 T, a periodic sequence of USPs (Fig. 2) with a duration of approximately 1 ns at half the peak power level and a repetition rate of 250 MHz (a repetition period of about 4 ns) was generated. This value (4 ns) corresponds to a feedback period in the generator estimated as $T_{rep} = (v_{gr}^{-1} + v_e^{-1})$, where v_e is the velocity of electrons in the beam, v_{gr} is the group velocity of a counter-propagating electromagnetic wave, and L is the length of the system. The following estimates of peak power of USPs were obtained in measurements with the waveguide coupler and the vacuum-tube detector for a single oscilloscope record of a microwave pulse train selected from a set of 50 records (Fig. 2, *a*): first — $P_1 = 0.21 \pm 0.04$ GW, second — $P_2 = 0.36 \pm 0.05$ GW, third — $P_3 = 0.49 \pm 0.07$ GW, fourth — $P_4 = 0.55 \pm 0.08$ GW, fifth — $P_5 = 0.52 \pm 0.08$ GW, sixth — $P_6 = 0.49 \pm 0.07$ GW, seventh — $P_7 = 0.52 \pm 0.08$ GW, and eighth — $P_8 = 0.34 \pm 0.05$ GW. The vacuum-tube detector was operated in the square-law mode, where its volt–watt characteristic may be approximated by a linear function. The corresponding conversion coefficients, which are defined as the ratio of the peak power of each microwave pulse to the electron beam power at time T_1, lie within the range of $K_{1-8} = 0.2{-}0.5$. In a series of 50 consecutive accelerator shots, the spread of microwave pulse amplitudes did not exceed 15%. The results of measurements of the peak USP power based on radio signals (Fig. 2, *b*) were as follows: peak powers $P_1 = 0.20 \pm 0.01$ GW, $P_2 = 0.35 \pm 0.03$ GW, $P_3 = 0.56 \pm 0.04$ GW, $P_4 = 0.64 \pm 0.05$ GW, $P_5 = 0.65 \pm 0.05$ GW, $P_6 = 0.59 \pm 0.04$ GW, $P_7 = 0.57 \pm 0.04$ GW, $P_8 = 0.35 \pm 0.03$ GW, and conversion coefficients K_{1-8}=0.3–0.6. The glow of a panel of gas-discharge lamps under the influence of microwave radiation had the form of a ring, which indicated selective excitation of a symmetrical wave TM_{01}.

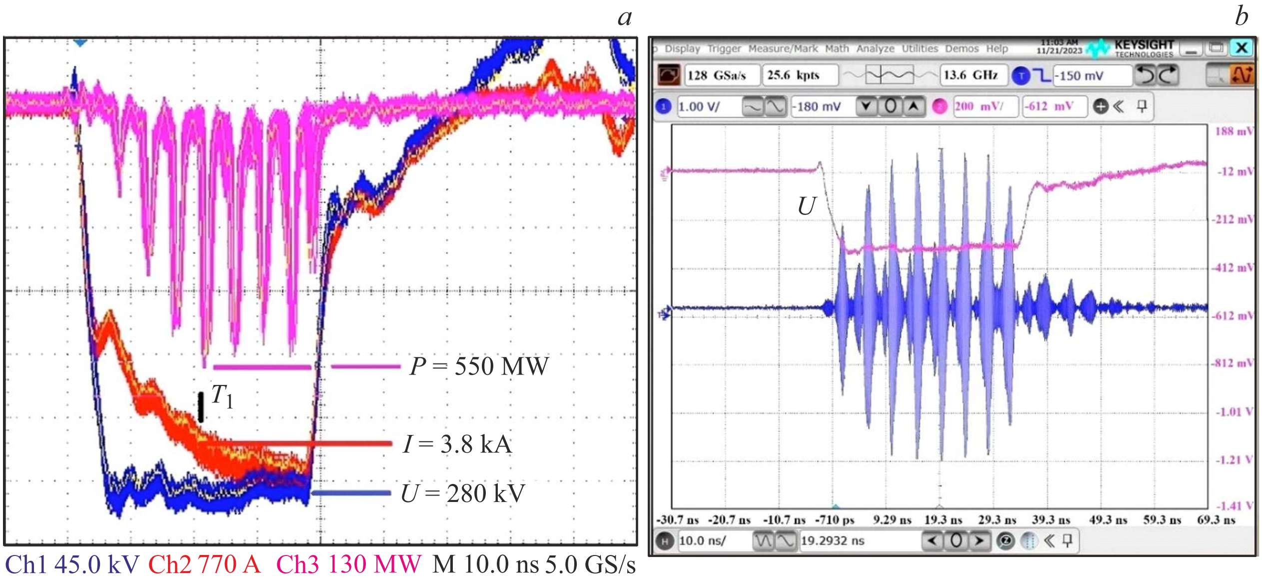

Figure 2. *a* — Oscilloscope records obtained in the accumulation mode in 50 successive shots of the electron accelerator operating with a repetition rate of 50 Hz; *b* — typical single oscilloscope record of a sequence of radio signals.

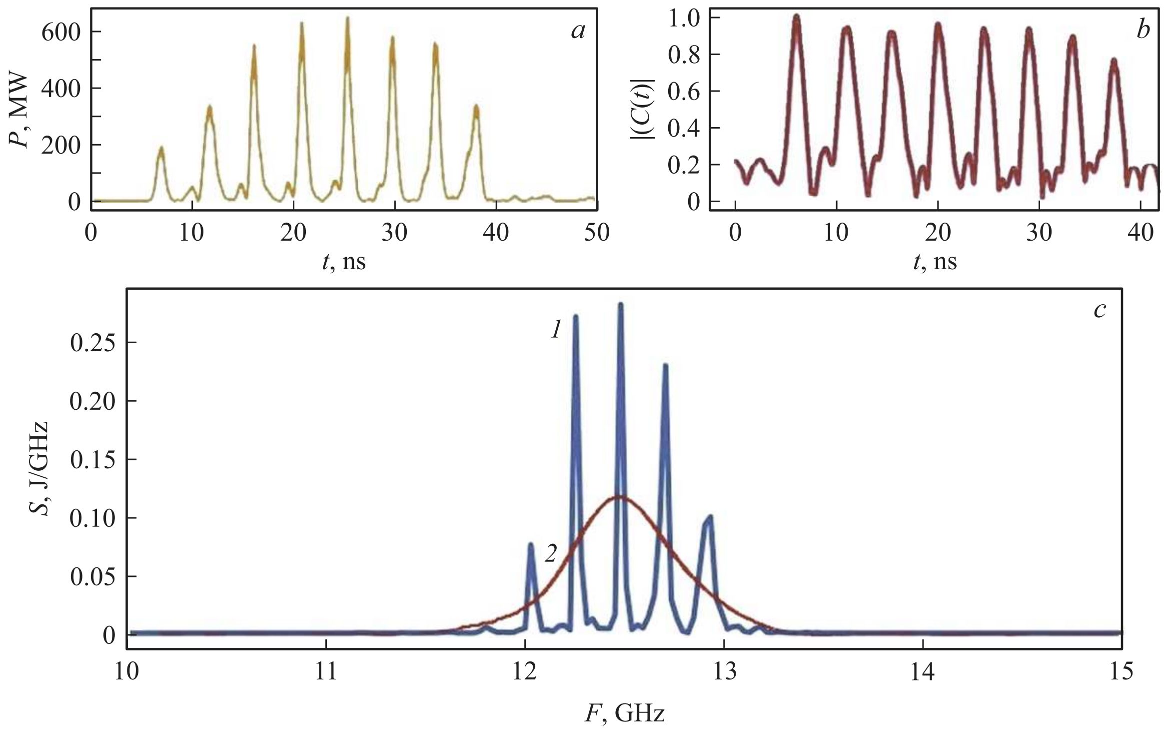

Figure 3. *a* — Temporal variation of the generation power averaged over the oscillation period ($T_{osc} = 1/F_{gen}$); *b* — envelope of the modulus of the normalized correlation function; and *c* — spectral energy densities of the entire USP sequence (*1*) and the pulse with the maximum amplitude (*2*).

The presence of a noticeable „pedestal“ in the oscilloscope records of detected microwave signals (Fig. 2, *a*), which forms at the moment of generation of the first USP and vanishes with the last pulse, may be associated with „noise“ generation in the intervals between adjacent pulses that has a wide and unstable spectrum. This generation may be caused by disturbances remaining in the electron beam after each USP generation event. It should be noted that a similar effect was also observed in numerical modeling, where spectral components were recorded well above 12 GHz and the power level of „noise“ generation did not exceed 50 MW.

Figures 3, $a-c$ present the results of processing of the sequence of radio signals shown in Fig. 2, b (including those obtained with the use of correlation function $C(t)$ and the Fourier transform).

The equality of frequency intervals $\Delta F \approx 0.25$ GHz (Fig. 3, c) between spectral lines is indicative of strict periodicity of microwave pulses ($T_{rep} \approx 4$ ns). The narrowness of spectral lines is also noteworthy. Taken together, these two facts provide evidence of coherence of generated USPs, which is also verified by the results of calculation of the autocorrelation function with the use of the recorded radio frequency signal. The central frequency of oscillations in each USP is approximately equal to 12.5 GHz.

It should be noted that the values of peak microwave power of USPs determined numerically within their entire sequence differ from those obtained in the experiment (the power for the first and second pulses is several times higher than the experimental values). This discrepancy is probably caused by a significant delay in the build-up of current of the electron beam emitted from the explosive emission cathode relative to the front of the accelerating voltage pulse. In the numerical calculation, the electron beam current increases synchronously with the accelerating voltage and reaches the required value of 4.5 kA in 5 ns. In contrast, the first and second pulses in the experiment (Fig. 2, a) formed when the accelerating voltage was already stabilized, while the electron beam current continued to rise. The reason for this desynchronization is that the necessary measures on optimization of the cathode assembly were not implemented. A purposeful refinement of its design should provide an opportunity to raise significantly the peak power of the first USPs.

The experimental confirmation of the existence of correlation between generated USPs is the most important result of the present study. In addition, the observed relatively slight lowering of the peak power of such pulses towards the end of a sequence suggests that the number of microwave pulses in a sequence may well be increased further both by shifting to a higher frequency range and by increasing the duration of electron beam current pulses.

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Conflict of interest

The authors declare that they have no conflict of interest.

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